A Systems-Level Perspective on Engine Ice Accretion

Ryan D. May

Vantage Partners, LLC

Ten-Huei Guo, Donald L. Simon

NASA Glenn Research Center

Presented to the ACGSC, Reno, NV
March 6-9, 2013

Overview

- Problem of Engine Power Loss
- Modeling Engine Icing Effects
- Simulation of Engine Rollback
- Icing/Engine Control System Interaction
- Detection of Ice Accretion
- Potential Mitigation Strategies
- Future Work

Problem of Icing Induced Power Loss

- More than 150 power loss events reported in last 20 years in High Ice Water Content conditions
  - Temporary or sustained power loss, uncontrollability, engine shutdown
- Many possible causes of power loss:
  - Compressor surge
  - Flame-out due to combustor ice ingestion
  - Damage due to ice shedding
  - Sensor icing
  - Engine rollback

Problem of Icing Induced Power Loss

- Ice crystals are believed to enter the core, melt, and accrete on engine components
- No pilot reports of weather radar returns
- No observations of airframe icing

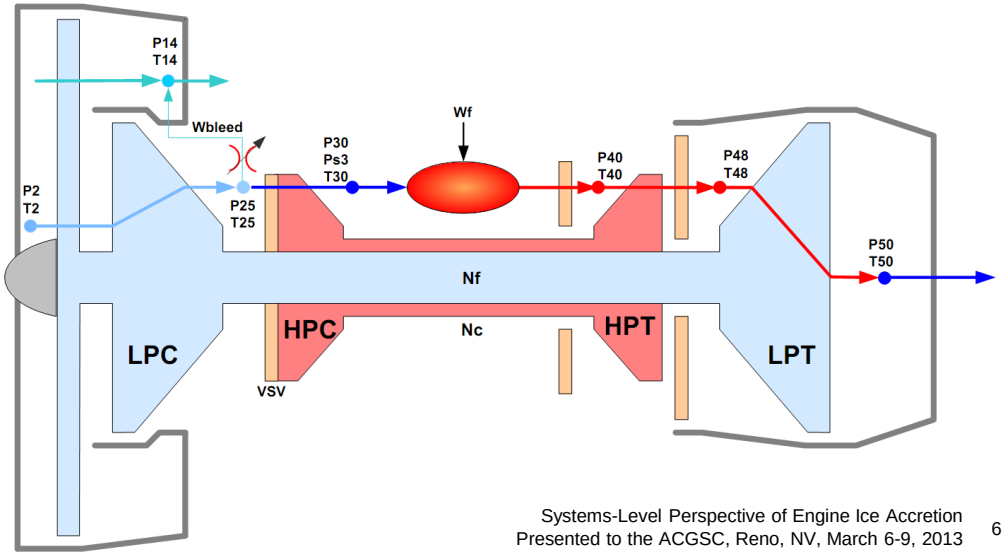
Video courtesy of NASA GRC

Our Approach

- Accept that ice does accrete in the engine core
- Focus on the impact of the icing on the engine's performance
  - Collaborative effort across NASA Glenn Research Center
    - » Controls and Dynamics Branch
    - » Turbomachinery Branch
    - » Icing Branch
- Develop models to study the conditions in which ice accretes (COMDES+NPSS+GlennICE)
- Use some of these results to develop "simplified" models

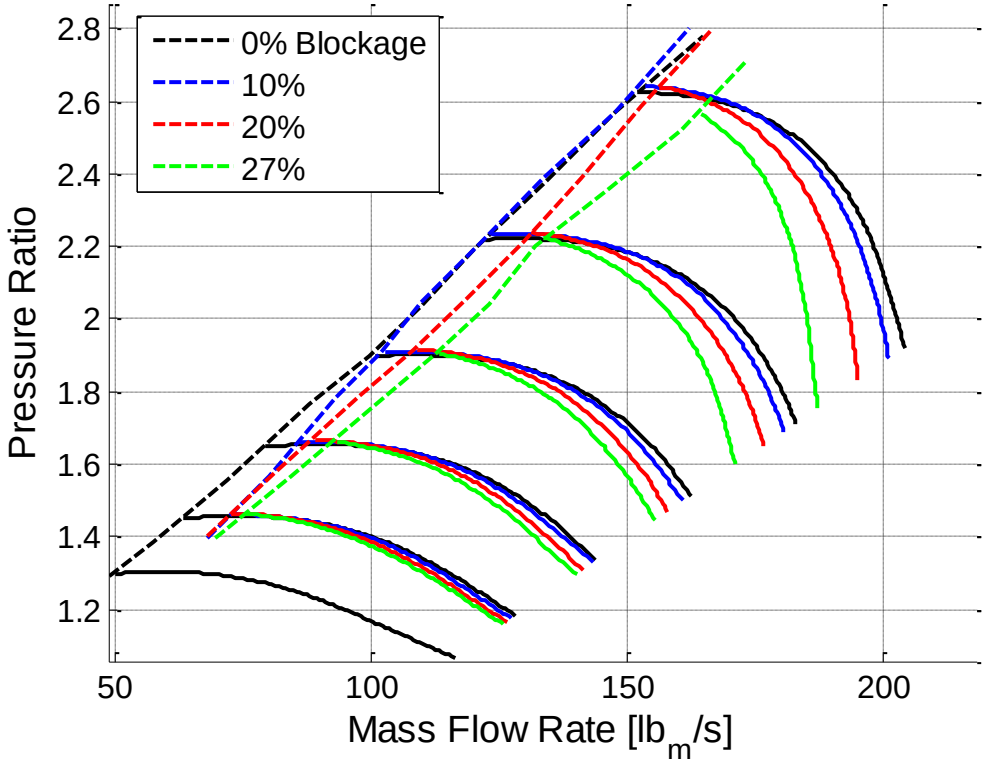
Modeling of Effect of Engine Icing

- C-MAPSS40k engine simulation
  - Commercial 40,000lb$_f$ thrust, high-bypass turbofan engine
  - Physics-based model
  - Realistic engine control system & sensor noise
  - Written in MATLAB/Simulink
  - Modular design
  - Publicly available to US citizens



Modeling of Engine Icing Effects

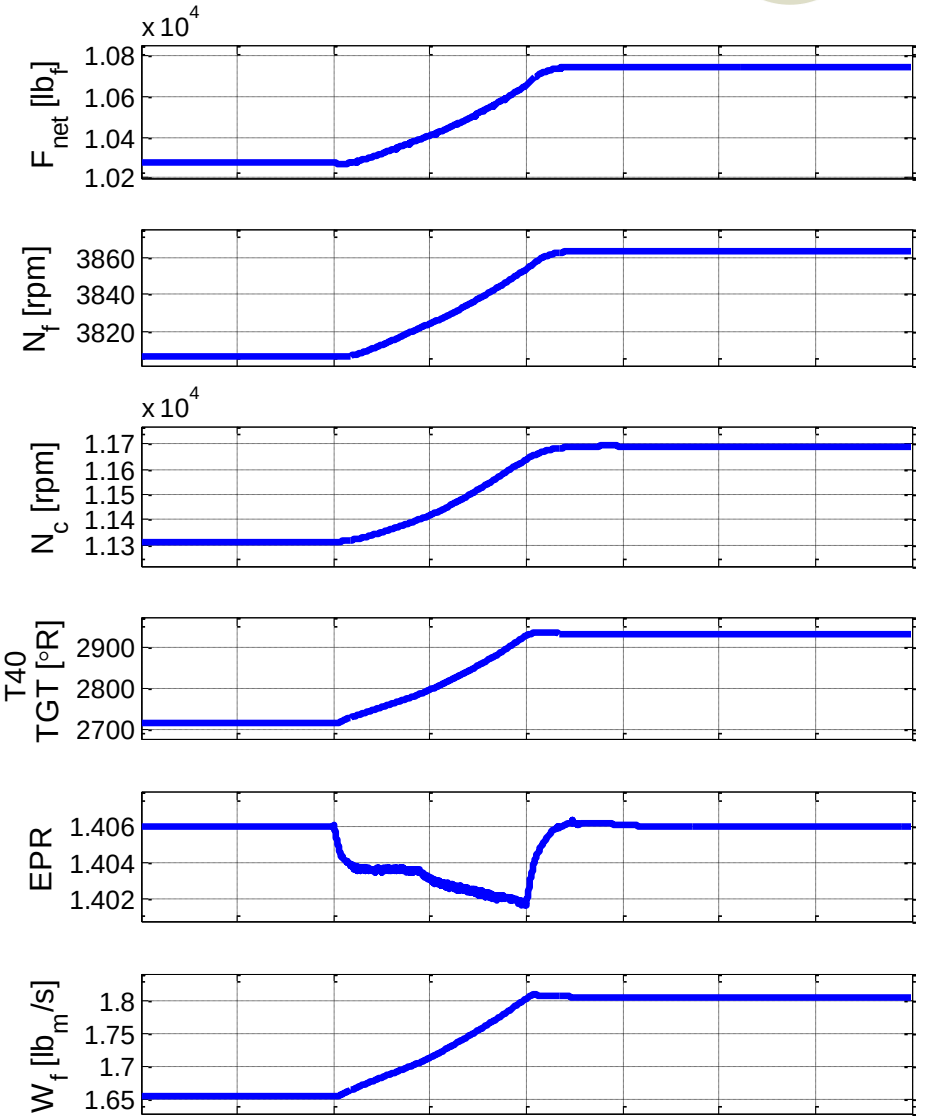
- Low Pressure Compressor (LPC) maps with various quantities of ice blockage in the 2nd row stator
- Integrated into C-MAPSS40k
  - Linear interpolation between maps



Underlying data from:
Jorgenson, P.C.E., Veres, J.P., May, R.D., Wright, W.B., "Engine Icing Modeling and Simulation (Part I): Ice Crystal Accretion on Compression System Components and Modeling its Effects on Engine Performance," 2011-38-0025, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0025

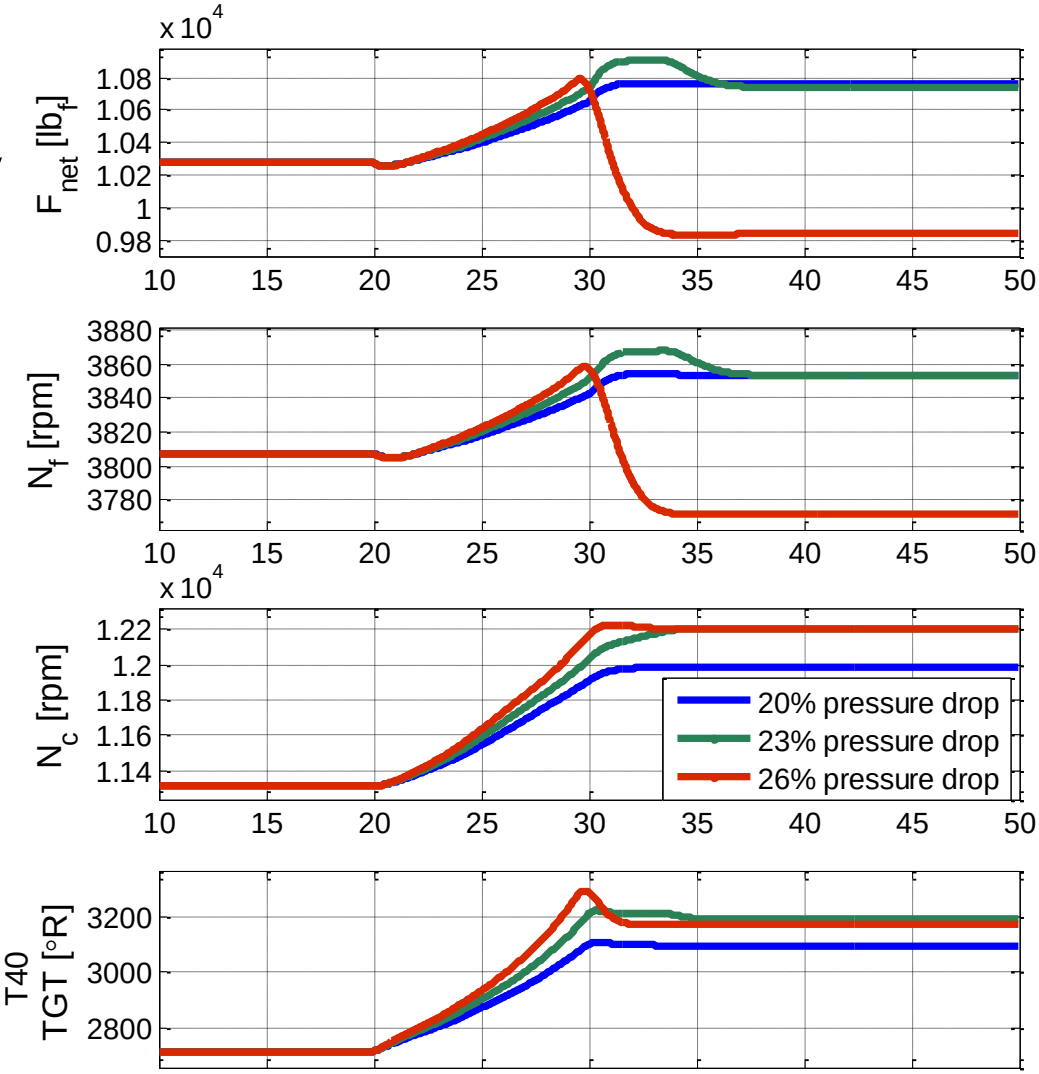
Simulation of Engine Performance during Ice Accretion

- Impact of Engine Icing
  - Start from nominal conditions and increase the blockage level
  - Move from nominal LPC map to 20% blocked map
- Effect:
  - Higher fuel flow rate required to maintain desired setpoint leads to increase in all other parameters
  - No Rollback event



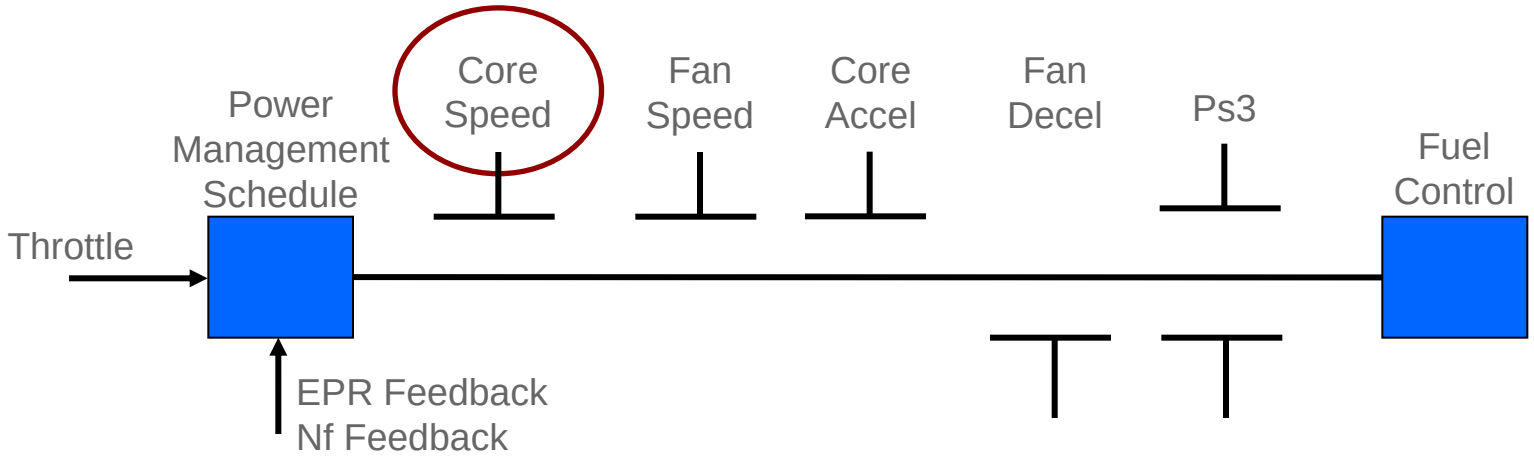
Simulation of Engine Rollback

- As blockage increases, eventually a rollback occurs
- Decrease in thrust
- Decrease in fan speed
- Increase in TGT



Engine Control System

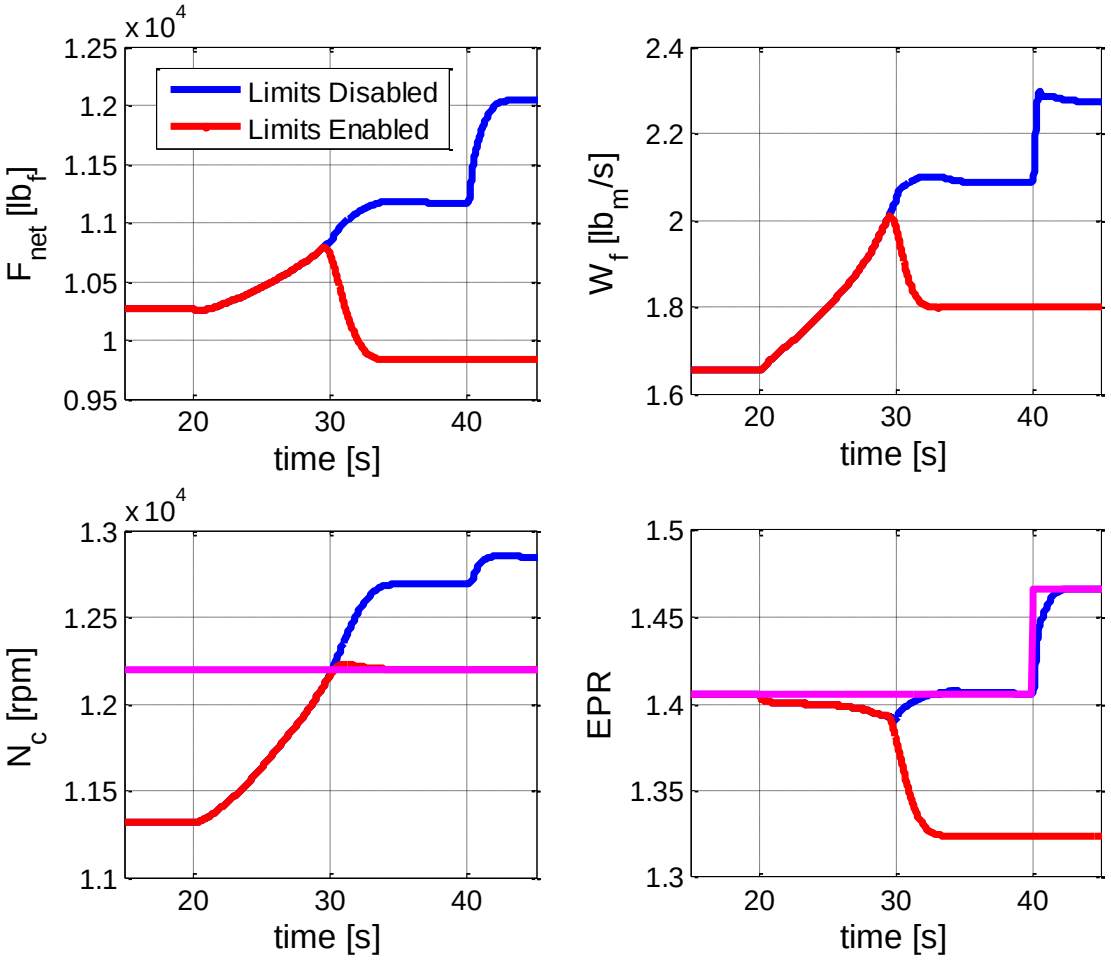
- Power Management
  - Responsible for holding current power level
- Protection Logic
  - Responsible for ensuring safe operation
  - Adjusts Fuel Flow to ensure limits are observed



Controller Response To Icing

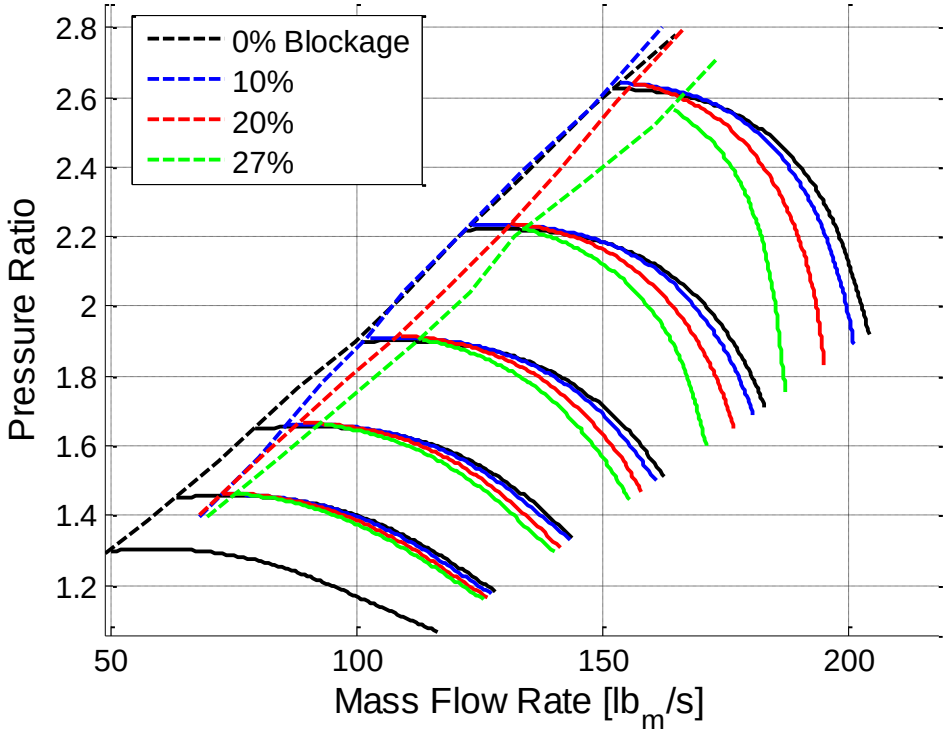
- Core speed limit prevents fuel flow rate from continuing to increase

- Normal operation of controller in the presence of blockage results in rollback



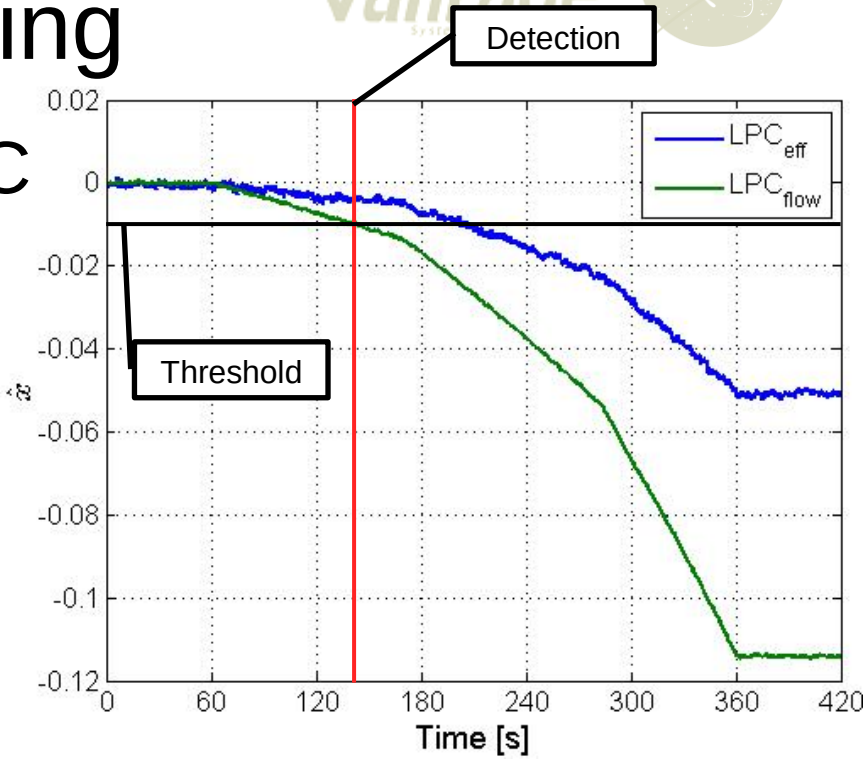
Detection of Engine Icing

- Typically 5 – 7 control sensors present in an engine
- Icing causes a change in the LPC operational characteristics
- Operate in conjunction with airframe devices to reduce chance of false-positive



Detection of Engine Icing

- Estimate the change in LPC "health" based on fan and core shaft speeds and look for a decrease in the flow capacity
- Linear estimator approach
  - Uses simple 1D interpolation
  - Low memory usage
  - Should be capable of operating real-time in typical FADEC



- Early Sim. Results:
  - False-Positive = 0.0%
  - True-Positive = 100.0%
  - Average Blockage Level at Detection = 6.80%

Mitigation of Engine Icing

- Ideally, completely avoid ice accretion
- If we can detect accretion can the engine controller act to mitigate the impact of the ice blockage?
- Potential mitigation strategies:
  - Operate actuators off-nominally to change operating point
    - » Close inter-compressor bleed valve or move HPC inlet guide vanes off schedule
  - Use existing airframe integration in novel ways
    - » Power take-off, Customer air bleed
  - Change shaft speed to cause ice to shed
- All of these approaches require iteration with an icing code to determine the effect of the new condition on ice accretion!

Future Plans

- Upcoming testing at NASA Glenn's Propulsion System Laboratory promises to provide validation of models and detection algorithm
- Develop mitigation strategies – iterate with the NASA GRC icing code to determine how the change in operating point impacts the accretion of ice & possible testing in PSL

Acknowledgements

- This work was funded by the NASA Aviation Safety Program's Vehicle Systems Safety Technologies Project

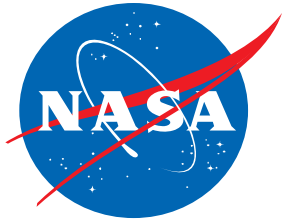
References

Jorgenson, P.C.E., Veres, J.P., May, R.D., Wright, W.B., “Engine Icing Modeling and Simulation (Part I): Ice Crystal Accretion on Compression System Components and Modeling its Effects on Engine Performance,” 2011-38-0025, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0025

May, R.D., Guo, T-H., Veres J.P., Jorgenson, P.C.E., “Engine Icing Modeling and Simulation (Part 2): Performance Simulation of Engine Rollback Phenomena,” 2011-38-0026, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0026

May, R.D., Simon, D.L., Guo, T-H., “Modeling and Detection of Ice Particle Accretion in Aircraft Engine Compression Systems,” AIAA Atmospheric Flight Mechanics Conference, Minneapolis, MN, Aug 13-16, 2012.

May, R.D., Guo, T.H., Simon, D.L., "An Approach to Detect and Mitigate Ice Particle Accretion in Aircraft Engine Compression Systems,“ ASME-GT2013-95049, to be published at the ASME TurboExpo 2013, San Antonio, TX, June 3-7, 2013.


NASA

Detection of Engine Icing

- Linear estimator – optimal unbiased least squares

$$y = Hx + \omega$$

$$\hat{x} = (H'R^{-1}H)^{-1}H'R^{-1}y$$

- Detection threshold can be chosen to obtain a desired false-positive rate
- As threshold increases the detection latency also increases